Regional Model Studies Nested in HYCOM. Application to the West Florida Shelf and the Cariaco Basin using ROMS

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LONG-TERM GOALS

Our long term goals are the development of robust model nesting strategies for coupling regional and global ocean circulation models and the implementation of data assimilation schemes suitable for the regional ocean models. From the perspective of advancing coastal ocean science we seek to improve our understanding on how the deep-ocean and the coastal ocean interact.

OBJECTIVES

This effort represents the USF contribution to the NOPP project, U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model, under the project component for demonstrating HYCOM as a provider of boundary conditions to nested regional and coastal ocean models. The specific objective of the USF component is to assess the impact of open boundary conditions from HYCOM on the dynamics and accuracy of a regional West Florida Shelf (WFS) model. Since deep-ocean currents are constrained to a large extent by the slope and shelf bathymetry, the benefit of using a large-scale ocean model as boundary conditions for shelf models requires explication, which is one of our objectives.

High frequency (HF) radar is a relatively new remote sensing technique with a large potential for constraining coastal ocean models, and this may provide for regional models the equivalent of altimetry for the global scale ocean models. Assessing the benefit of HF radar currents data on the WFS model via assimilation using an ensemble to prescribe the model error covariance is another objective.

In the Cariaco basin (Venezuela) model, our objective is to study the influence of the large-scale, open ocean currents on the basin hydrography, in particular the processes that affect the ventilation of the basin. Accurate boundary conditions provided by HYCOM are then essential for this study.

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APPROACH

In order to emphasize the role of the boundary conditions on the WFS model, we conducted the following three model experiments:

- WFS ROMS nested in temperature and salinity climatology. The monthly temperature and salinity climatology of Ruoying He (personal communication), which is based on the data set of Levitus and Boyer (1994) and Levitus et al (1994), is used. For the elevation we used a zero-gradient boundary condition, and for the velocity, temperature, and salinity we used a radiative boundary condition (Marchesiello et al, 2001).

- WFS ROMS nested in NAT HYCOM temperature and salinity. The daily temperature and salinity from the NAT HYCOM model (Chassignet et al., 2007) are used as boundary conditions in this experiment instead of climatology.

- WFS ROMS fully nested in NAT HYCOM. Not only temperature and salinity are used in this experiment, but also the elevation and velocity of the NAT HYCOM.

The approach for the assimilation experiments consists of estimating the model error covariance by an ensemble model run with perturbed wind forcing, which is assumed to be the primary error source. All model states produced this way will have different surface currents reflecting uncertainties in the model results. The radial HF-Radar current fields are assimilated. The two-day model forecast is compared to the not yet assimilated surface current observations to determine if the assimilation generated spurious variability. The model results are also compared to ADCP velocity at depth to assess the effectiveness of the vertical projection.

The Cariaco basin model is nested in the North Atlantic HYCOM and the NCODA global HYCOM. The results obtained using these two boundary conditions are compared and validated against independent data, in order to choose the boundary conditions that lead to a better simulation of the Cariaco basin. Year-long simulations are used to study the annual cycle of the Cariaco basin.

The model nesting on the WFS and the data assimilation are being performed by Alexander Barth. The Cariaco nesting is performed by Aida Alvera-Azcárate.

WORK COMPLETED

The Regional Ocean Modeling System (ROMS; http://www.myroms.org) solves the three-dimensional, free surface, hydrostatic, primitive equations (Shchepetkin and McWilliams, 2005). The WFS model domain is shown in Figure 1. The horizontal resolution of its curvilinear grid ranges from 4 km near the coast to 10 km near the open boundary. The vertical is discretized in 32 levels.

The atmospheric forcings include air temperature, relative humidity, cloud fraction, and short-wave radiation from NOGAPS (Navy Operational Global Atmospheric Prediction System) and an optimal interpolated (OI) wind product combining NCEP NAM winds (National Centers for Environmental Prediction, North American Mesoscale Model) with *in situ* wind measurements (He et al, 2004). The model SST is relaxed to a cloud-free, optimal interpolated SST (He et al 2003) based on AVHRR (Advanced Very High Resolution Radiometer), GOES (Geostationary Operational Environmental Satellites), MODIS (MODerate Resolution Imaging Spectroradiometer), and TMI (TRMM Microwave

Imager), as described in Barnier et al (1995). This model is nested in to the 1/12 Atlantic HYCOM and into climatology for the West Florida Shelf.

One central problem in sequential data assimilation is to produce a balanced ocean state. Otherwise high-frequency transient motions are created which can degrade the model solution. In free-surface models, this high-frequency variability is often associated with surface gravity waves. A filter to reduce the inertial-gravity waves is derived using the analytical solution of the shallow water equation for a constant water depth by explicitly prescribing the wave amplitudes to zero. It was show that this filter conserves the potential vorticity. This method is extended to arbitrary bottom topography using a variational approach by including the requirement that the flow follows isobaths as a weak constraint (Barth et al. 2007).

Different strategies to assimilate HF-Radar surface currents are considered: use of an ensemble where each member represents a time average to exclude high-frequency variability from the ensemble, the use of a explicit inertia-gravity wave filter (Barth et al. 2007) and the inclusion of the wind stress in the assimilation state vector (since the adopted ensemble approach allows to take the covariance between observed surface currents and wind stress into account).

The Cariaco basin model (Figure 2) is also based in ROMS, and the atmospheric forcings are obtained from NCEP. A hindcast of the year 2004 was completed. The model has a resolution of 1/60° in both the meridional and the zonal directions, and has 32 vertical levels. The 2004 hindcast used the Atlantic and global implementations of HYCOM, and the results were compared with in situ data (Figure 2).

RESULTS

Benefit of model nesting

The Gulf of Mexico Loop Current (LC) is the main large-scale ocean feature in the WFS domain. Figure 3 shows the mean sea surface height (SSH) in April 2004 for the three model configurations relative to the AVISO sea surface height anomaly (Ducet et al, 2000) added to the MICOM mean SSH (Chassignet and Garraffo, 2001), all averaged over the same time period. April 2004 was chosen because the LC was very stable during this month (*i.e.* there was no eddy shedding and the LC trajectory was stable). *A priori*, the model forced with climatology should be able to reproduce the deep-ocean currents in this situation. The SSH gradients are indicative of the LC velocity and the LC SSH maximum is related to LC volume transport, since the SSH is a proxy for the stream function of the upper ocean. In the model run with climatological forcings, the LC is too weak. Its SSH maximum is, with 0.3 m (upper left panel of Figure 3, significantly lower than the maximum SSH derived from altimetry and MICOM (0.70 m; lower right panel of Figure 3).

By using HYCOM temperature and salinity (upper right panel of Figure 3), the model is able to represent the LC much more realistically. In particular, the maximum SSH (0.62 m) is much closer to the altimetry, but is still too small. The NAT HYCOM assimilates altimetry observations, and the WFS ROMS model benefits from those improved boundary conditions. By using also NAT HYCOM velocity and elevation (lower left panel of Figure 3), the LC strength (0.66 m of maximum SSH) comes closest to the observations. This indicates that the density field alone is not sufficient to completely represent the LC transport.

The model results obtained by the three nesting configurations are compared with a series of moorings located on the WFS (see Figure 1). Figure 4 shows the near-bottom (19 m) temperature at station C11. The model forced with climatology is too cold during summer and has the highest RMS error of all three model experiments. During summer, the model experiment forced with climatology develops an unrealistic southward coastal current. This current exits the model domain near Key West (Figure 1) and is determined by the model boundary conditions. A persistent upwelling in the bottom Ekman Layer is associated with this current and therefore we observe this temperature bias in the model simulation with climatology. The best temperature time series is obtained with ROMS nested in HYCOM which shows a more realistic current variability.

In order to assess the overall performance of the different nesting experiments compared to *in situ* temperature, the RMS errors at all available depths at stations C11, C12, C13, C14 and C16 were computed. The average model RMS error with climatology was 0.69˚C. This result is improved when HYCOM temperature and salinity are used as boundary conditions since the error is reduced to 0.62˚C. The best results, with an RMS error of 0.58˚C, were obtained with the model fully nested in HYCOM.

Data Assimilation

Each of the tested assimilation strategies shows an improvement of the 2-day forecasted surface currents and currents at depth (compared with ADCP data). The best model results are obtained when all the strategies (see the work completed section) are used together.

The observed zonal velocity along the with model zonal velocity without and with assimilation are shown in the first three panels of Figure 5. The last three panels of this figure show the corresponding fields of the meridional velocity.

The free model is already in good agreement with the observations at this station. Not only the events with barotropic flow are in good agreement with the observations, the free running model is also able to represent to some degree the baroclinic events related to strong currents. The time averaged RMS error between observations and model simulation for different depths is shown in Figure 6. The error reduction of the model currents is indeed largest at the surface but the error is also reduced over the entire water column. The improvement in relative terms can be quantified using the mean square error skill score which is 0.33 near the surface and 0.18 near the bottom.

At station C12, the model shows an unrealistic northwestward current from April to May (Figure 7). In the model simulation with data assimilation, the currents during this period are reduced to a more realistic level according to the ADCP observations. Figure 6 shows the time averaged RMS errors. As expected, the RMS error is most significantly reduced at the surface and its impact decreases with depth. Near the bottom (at 40 m depth), the assimilation of the surface currents has almost no impact at this station.

Cariaco model

The comparison of the model temperature to in situ data reveals a cold bias in the model forced with NAT HYCOM boundary conditions (see observed data in Figure 9 and model results in Figure 10a). The model forced by the NCODA global HYCOM represents the basin's temperature much more accurately (Figure 10b). The average temperature of the NAT HYCOM at the Cariaco model northern boundary is about 2˚C colder than climatology along the whole water column (Figure 11a), a bias that is eventually transferred to the Cariaco model. The boundary conditions provided by the NCODA global HYCOM match the climatological temperature closely (Figure 11b), and therefore the bias in the Cariaco model is greatly reduced. The NCODA global HYCOM has therefore been chosen to provide boundary values for the Cariaco model, and will be used in our future runs. An example of the Cariaco model nested in the global HYCOM can be seen in Figure 12.

IMPACT/APPLICATIONS

The results of this work show that the boundary conditions have an influence not only on large-scale deep-ocean features such as the Loop Current (LC), but also on the shelf properties even if the open boundary is located in the deep-ocean.

Gradients in the climatology appear to be too weak to support the LC with a realistic strength and path. Using NAT HYCOM temperature and salinity, the characteristics of the LC are much improved compared to climatological forcing but still weaker than the LC observed from altimetry. The best results concerning the LC position and strength were obtained if also the velocity and elevation are taken into account during the nesting.

On the shelf, stratification and currents are mainly conditioned by atmospheric heat and momentum fluxes. Although the atmospheric forcings are the same in all three nesting experiments, the results on the shelf differ and we were able to show that the choice of the boundary and initial conditions have a noticeable impact on the shelf solution. The climatological boundary values created an unrealistic shelf current since the open boundary intersects the shallow isobaths.

Different variants of the implemented assimilation scheme have been tested using a time-average ensemble, a filter to reduce surface-gravity waves and an extended state vector including wind stress. Each of the techniques improves the 2-day model forecast compared to not yet assimilated surface current measurements. The best model simulation is obtained when all of the variants are used together showing that the obtained benefit is not mutually exclusive.

HF-Radar currents are a promising data set to constrain the circulation of coastal models providing significant coverage over the WFS model domain. HF-Radar currents estimates correlate well with more traditional ADCP measurements, even during extreme events such as hurricanes.

The model of the Cariaco basin nested in global HYCOM improves our knowledge of the dynamics of this system. The Cariaco Basin is an important place for paleo-climate studies, which use the high-quality sediment record stored at the basin's seabed. To understand how the past climate affected the sediment record it is essential to understand the present conditions within the basin and how the basin hydrodynamic characteristics are affected by open ocean processes. This is realized through the nested model presented here.

TRANSITIONS

The WFS model nested in HYCOM is now run at a daily basis and the full model results can be accessed and visualized at http://ocgmod1.marine.usf.edu/WFS/. In particular, arbitrary horizontal and vertical section can be displayed (Figure 13).

The Center of Ocean Technology in collaboration with the College of Marine Science develops and deploys the Bottom Station Ocean Profiler (BSOP). This instrument measures temperature and salinity and it samples the water column by changing its buoyancy. The measurements are transferred in real time and are archived. A web interface (Figure 14) allows to visualize the temperature and salinity data from BSOP and to compare these observations with the corresponding values from the WFS ROMS model. The model results are now also used to plan BSOP deployments.

Jointly the FWRI, the model currents are used to computed the trajectory of simulated drifter originating in location with measured *Karenia brevis* cell count data. The interface to these forecasts is shown in Fogire 15.

RELATED PROJECTS

The impact of different boundary conditions is done within the HYCOM CODAE project. The intercomparison will be extended to different models within this project.

The WFS modeling system will be used by Center for Red-tide Prediction (CPR) in collaboration with J. Walsh (USF) for biological modeling and C. Heil (FWRI) for K. brevis observations, a goal of CPR is to provide quantitative red tide information for use by State of Florida environmental managers.

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Alvera-Azcárate, A., Barth, A., Beckers, J.-M. and Weisberg, R. H. (2007). Multivariate reconstruction of missing data in sea surface temperature, chlorophyll and wind satellite fields. Journal of Geophysical Research. 112, C03008, doi:10.1029/2006JC003660. [Published, refereed].

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Barth, A., Alvera-Azcárate, A., Weisberg, R. H., 2007c. Assimilation of High-Frequency Radar Currents in a Nested Model of the West Florida Shelf. [Submitted, refereed]

Barth, A., J.-M. Beckers, A. Alvera-Azcárate, and R. H. Weisberg (2007), Filtering inertia-gravity waves from the initial conditions of the linear shallow water equations, Ocean Modelling, 19, 204–218. [published, refereed]

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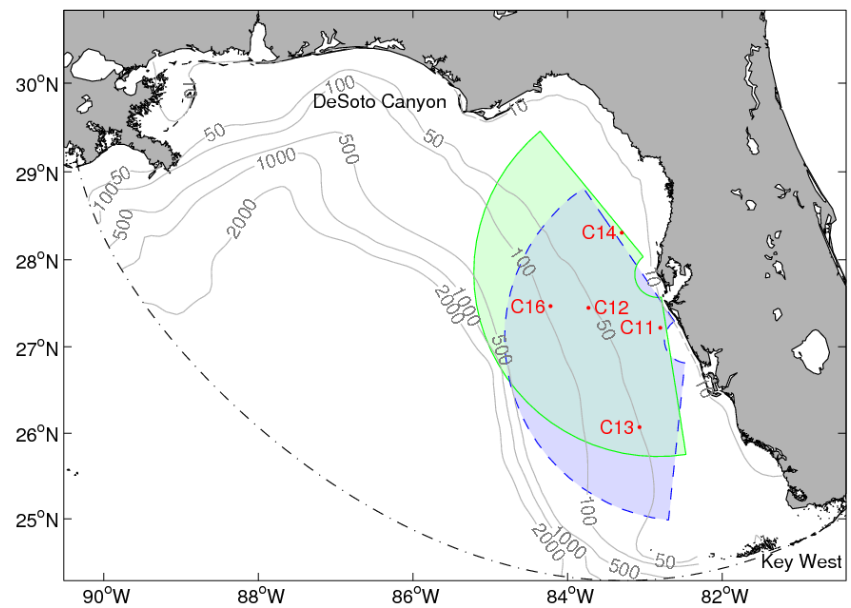

Figure 1.

Figure 1: The West Florida Shelf. The dash-dotted line shows the open boundary of the WFS ROMS domain and isolines represent the depth of the model bathymetry (in m). The regions in green and blue delimited by the solid and dashed lines represent the coverage of Redington and Venice CODAR stations respectively. The dots show the locations of in situ measurements used for validation along with their names.

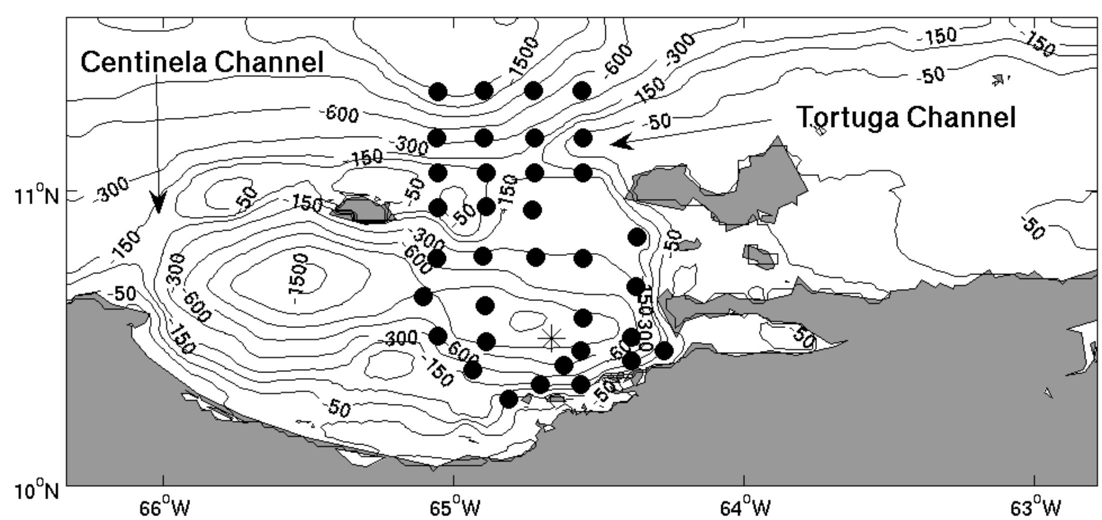

Figure 2.

Figure 2: Cariaco Basin (Venezuela). The isolines represent the bathymetry, and the dots and asterisk represent the in situ observations used for validation of the model.

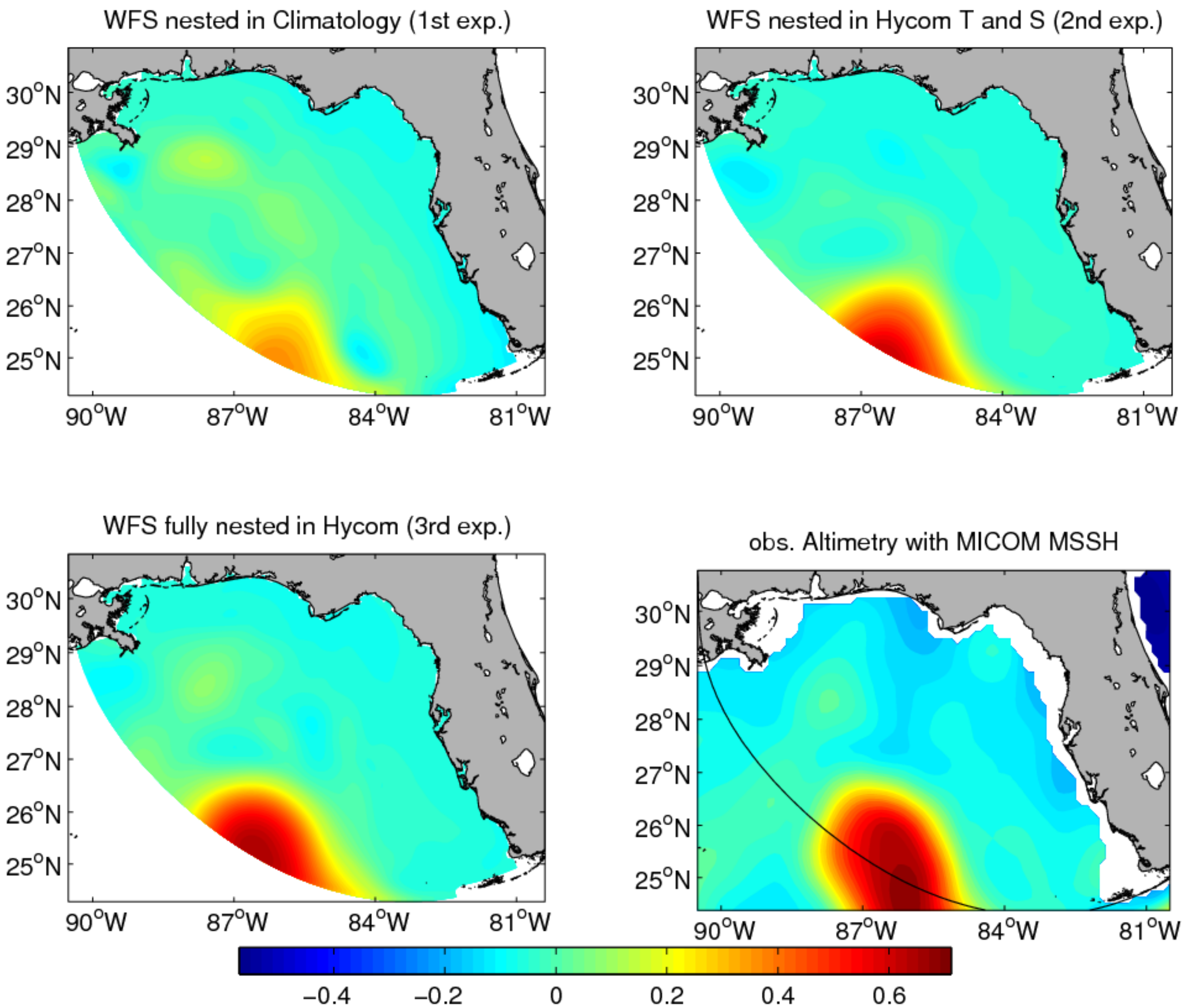

Figure 3.

Figure 3: Mean sea surface height (in m) on April 2004 from the model (first three panels) and observations (lower right panel).

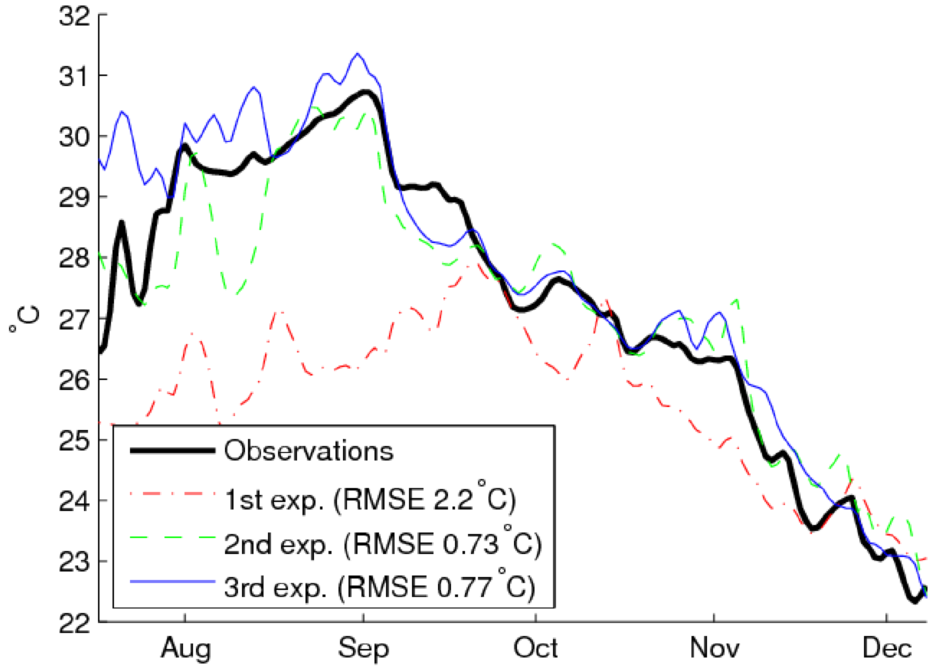

Figure 4.

Figure 4: Observed temperature time series of station C11 at 19 m depth and temperature of the WFS ROMS nested in climatology (1st exp.), WFS ROMS nested in NAT HYCOM temperature and salinity (2nd exp.) and WFS ROMS fully nested in NAT HYCOM (3rd exp.).

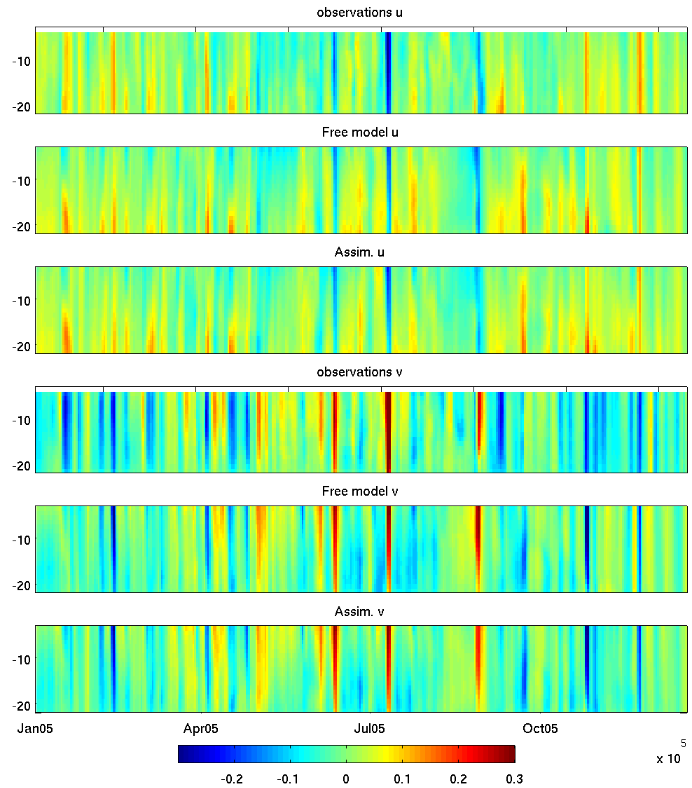

Figure 5.

Figure 5: Zonal (u) and meridional velocity (v) at station C10 of the ADCP observations, of the free model run and of the model run with data assimilation as a function of depth (m) and time. Velocities are expressed in m/s.

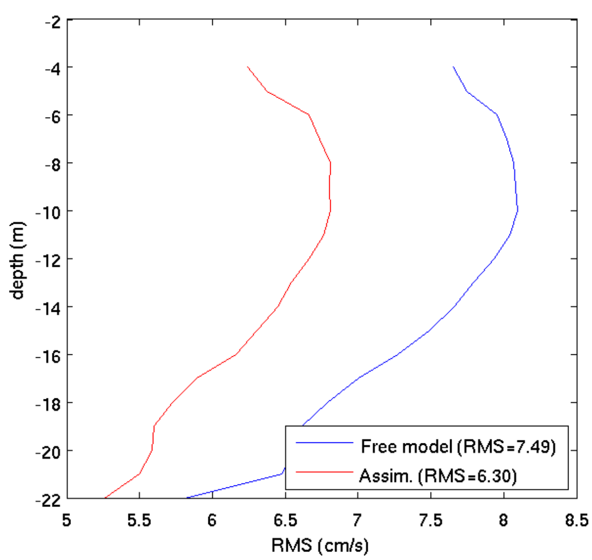

Figure 6.

Figure 6: Time averaged RMS error between ADCP observations at C10 and the model run without assimilation (free model) and with assimilation. The RMS values in the legend represent the depth average RMS error in cm/s.

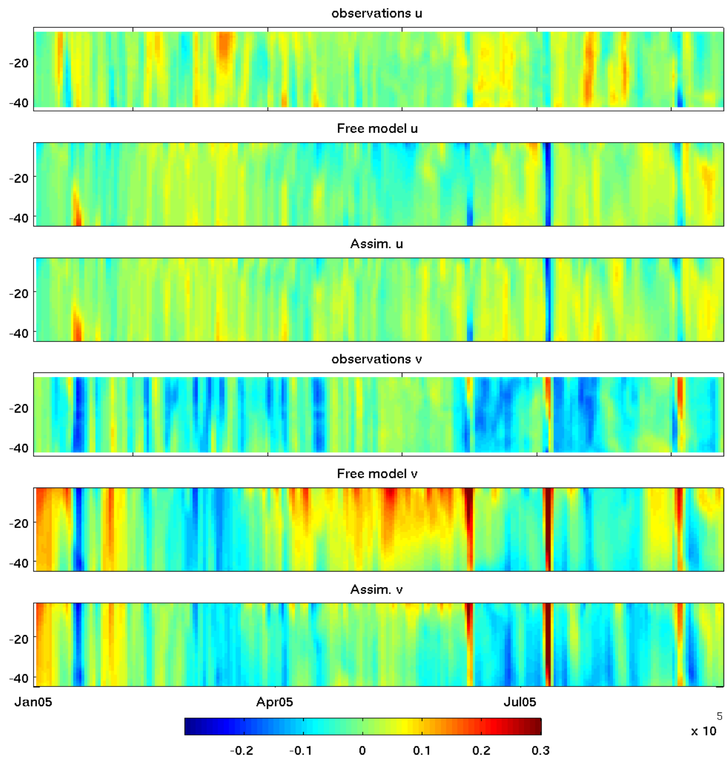

Figure 7.

Figure 7: Zonal (u) and meridional velocity (v) at station C12 of the ADCP observations, of the free model run and of the model run with data assimilation as a function of depth (m) and time. Velocities are expressed in m/s.

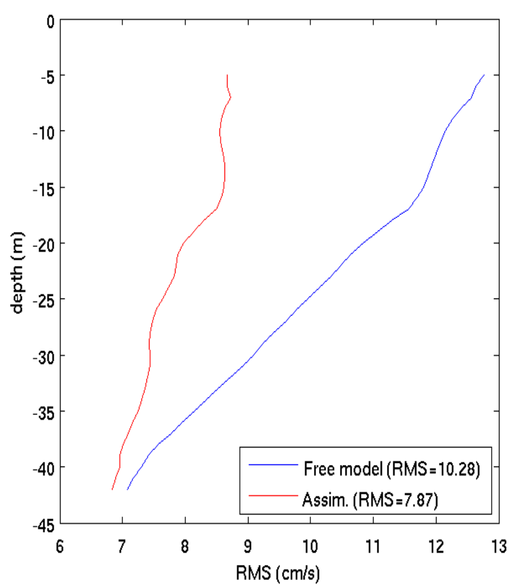

Figure 8: Time averaged RMS error between ADCP observations at C12 and the model run without assimilation (free model) and with assimilation. The RMS values in the legend represent the depth average RMS error in cm/s

Figure 8.

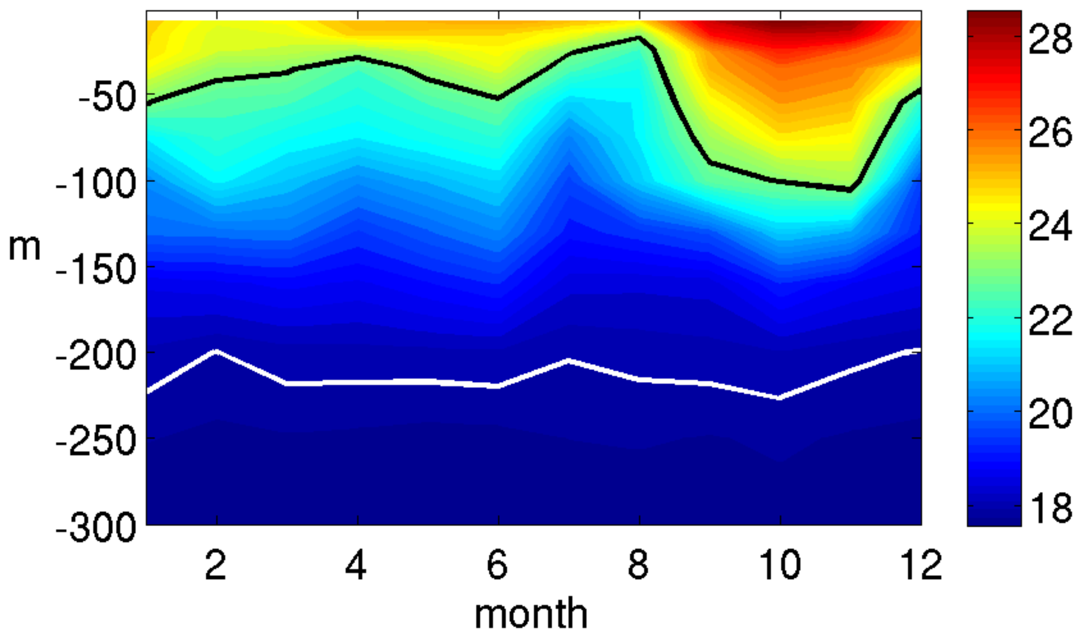

Figure 9.

Figure 9: Observed temperature annual cycle in the Cariaco basin. The position of this measure is marked by an asterisk in Figure 2.

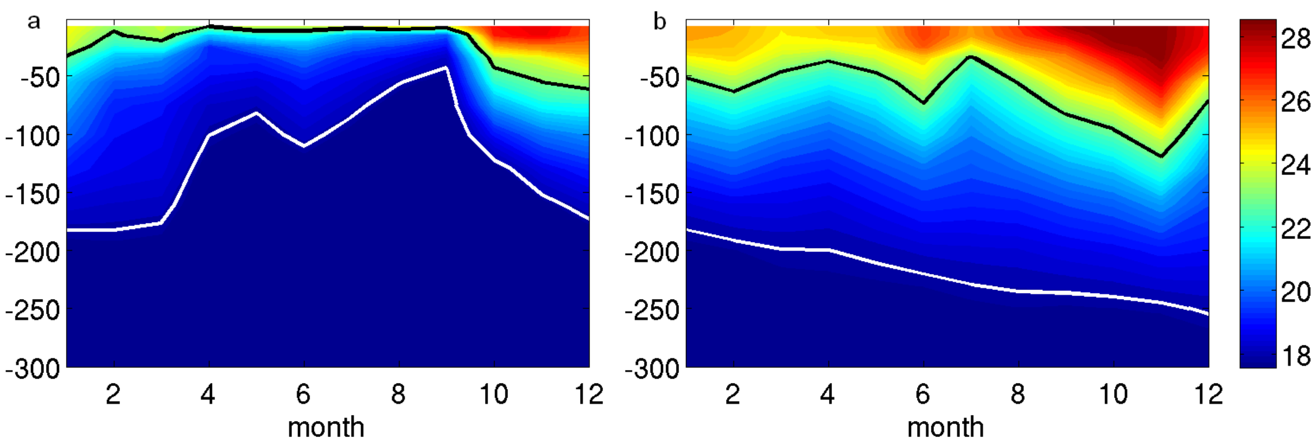

Figure 10.

Figure 10: Model temperature in the Cariaco basin (at position marked with an asterisk in Figure 2) using (a) NAT HYCOM boundary conditions and (b) global NCODA HYCOM boundary conditions.

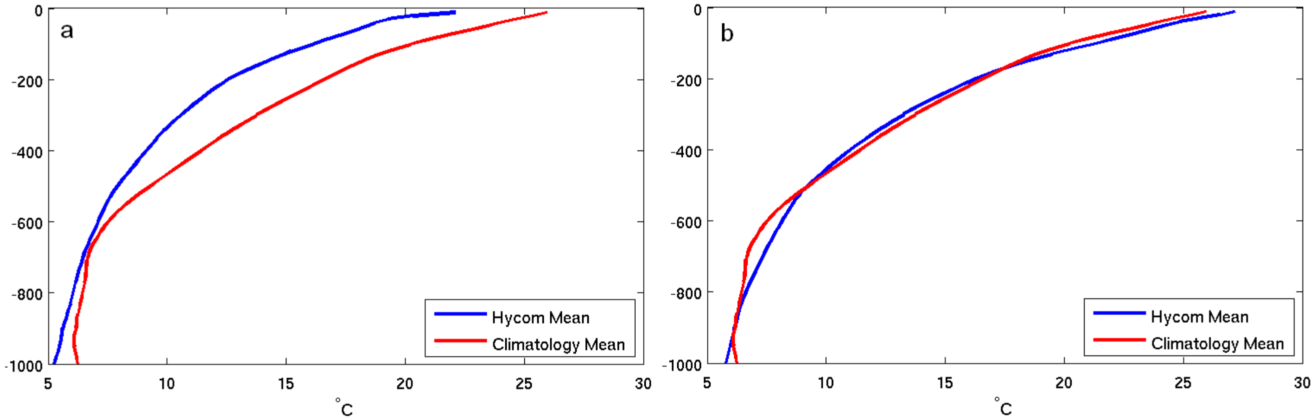

Figure 11.

Figure 11. Comparison between climatology and (a) NAT HYCOM temperature at the northern boundary of the Cariaco basin; (b) global NCODA HYCOM temperature at the northern boundary of the Cariaco basin.

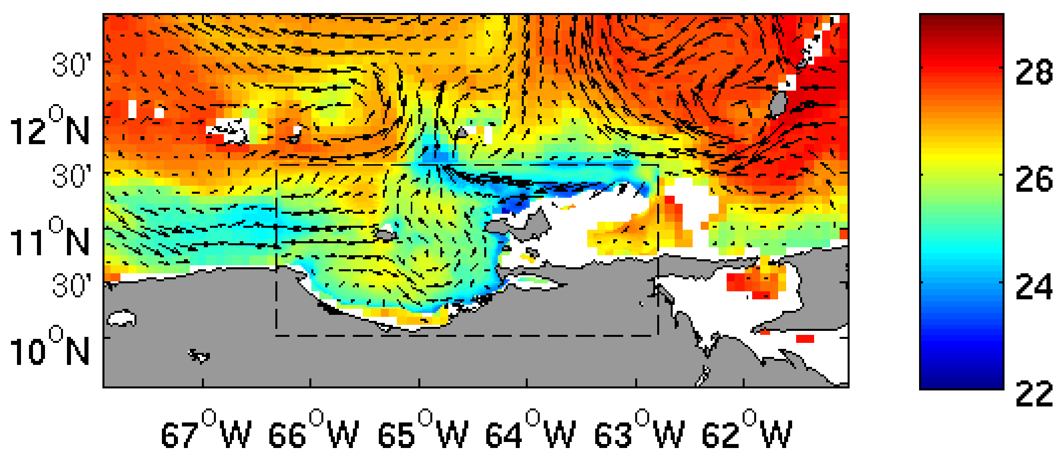

Figure 12.

Figure 12: Cariaco model temperature and currents at 20 m depth on 30 April 2004 (inside the dashed box) and global NCODA HYCOM temperature and currents at the same depth and date (outside the dashed box).

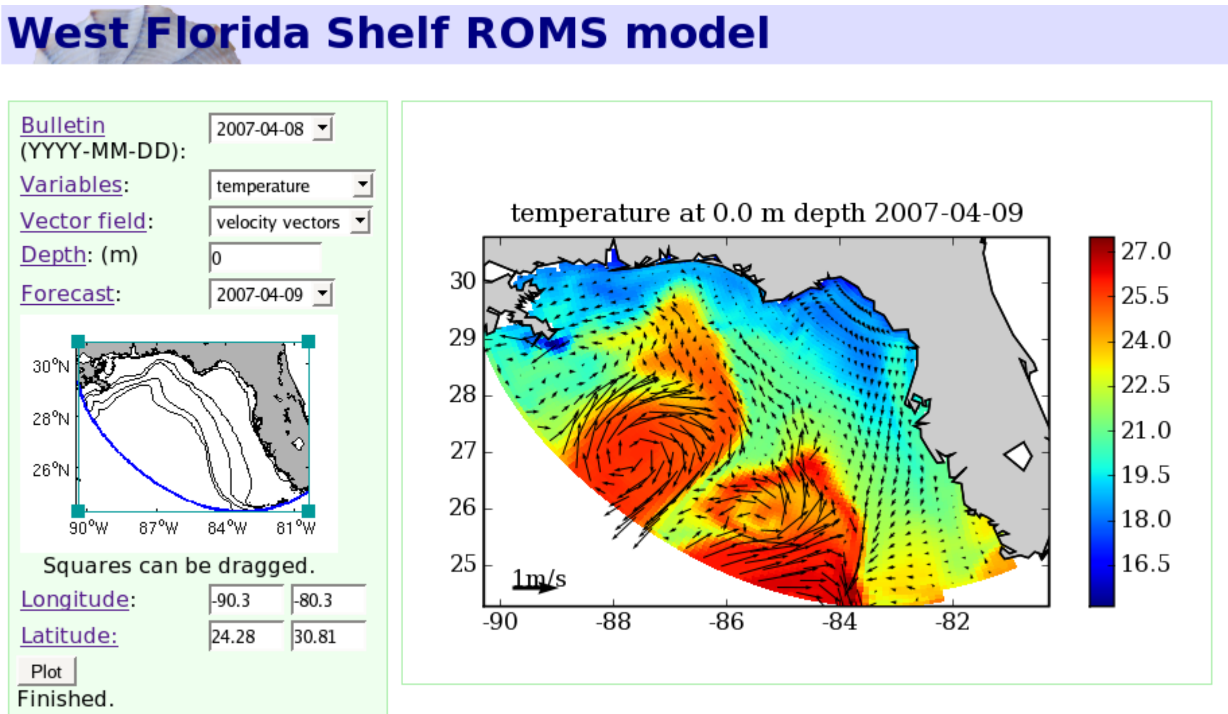

Figure 13.

Figure 13: Model sea surface temperature and surface currents on 8 April 2007 obtained from the web interface.

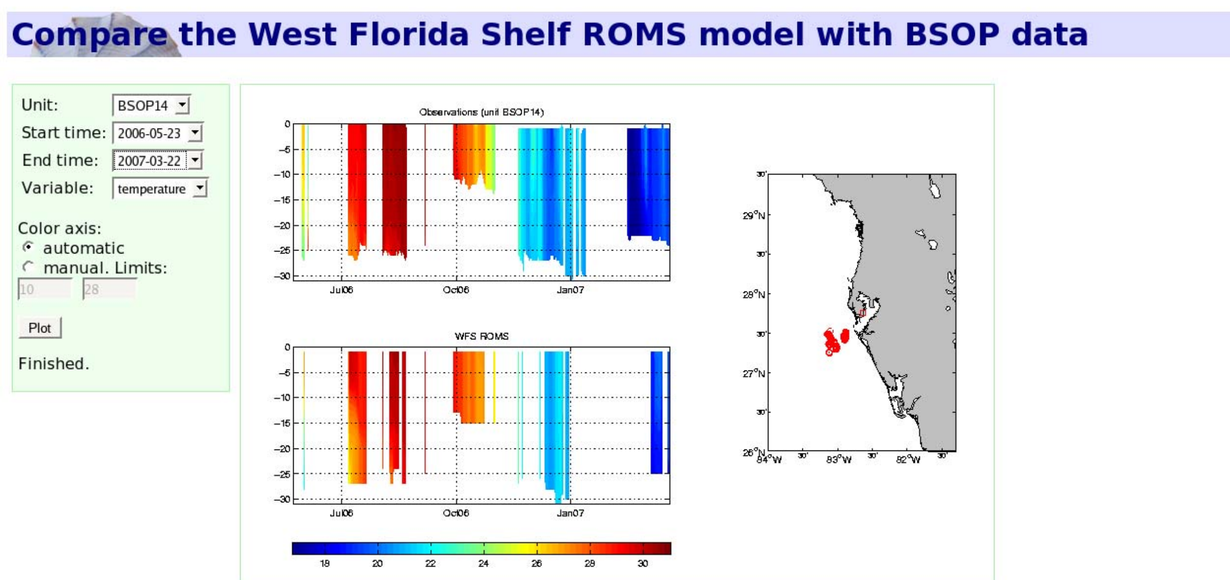

Figure 14.

Figure 14: Comparison of BSOP temperature (top) and the model results (below). These comparisons are accessible through a web-interface and are updated automatically.

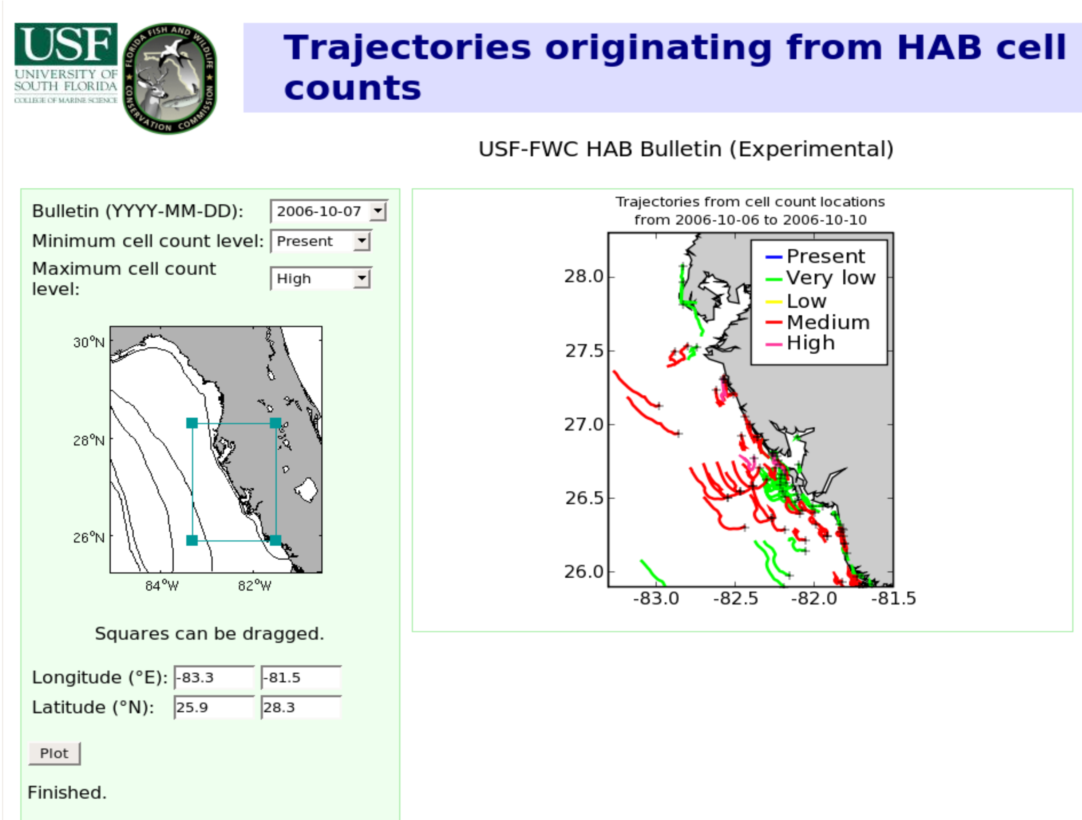

Figure 15.

Figure 15: Projected trajectories of water with a measured cell count of K. brevis using the model currents the WFS ROMS nested in HYCOM. This product is accessible through a web-page and automatically updated.